

# COOLING FLOW STAR FORMATION AND THE APPARENT STELLAR AGES OF ELLIPTICAL GALAXIES

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## ABSTRACT

Simple theoretical arguments indicate that cooled interstellar gas in bright elliptical galaxies forms into a young stellar population having a bottom-heavy, but optically luminous IMF extending to  $\sim 2 M_{\odot}$ . When the colors and spectral features of this young population are combined with those of the underlying old stellar population, the apparent ages are significantly reduced, similar to the relatively young apparent ages observed in many ellipticals. Galactic mergers are not required to resupply young stars. The sensitivity of continuous star formation to  $L_B$  and  $L_x/L_B$  is likely to account for the observed spread in apparent ages among elliptical galaxies. Local star formation is accompanied by enhanced stellar  $H\beta$  equivalent widths, stronger optical emission lines, more thermal X-ray emission and lower apparent temperatures in the hot gas. The young stars should cause  $M/L$  to vary with galactic radius, perturbing the fundamental plane of the old stars alone.

*Subject headings:* galaxies: elliptical and lenticular – galaxies: evolution – galaxies: cooling flows – galaxies: interstellar medium – x-rays: galaxies

## 1. INTRODUCTION

Traditionally, elliptical galaxies have been regarded as ancient stellar systems in which evolutionary processes have been exhausted or completely arrested. However, recent observational and theoretical developments have led to a reassessment of both the ages of the stars in ellipticals and the ages since the stellar system merged into its current configuration. Our objective here is to illustrate the possibly important contribution to the apparent global stellar age in ellipticals due to a population of young, intermediate mass stars formed from cooled interstellar (cooling flow) gas. We also review the related structural history of ellipticals. The high degree of structural regularity among ellipticals has been used to argue that they were among the first galaxies that formed. Of most interest are the remarkable thinness of the fundamental plane (Djorgovski & Davies 1987;

Dressler et al. 1987; Renzini & Ciotti 1993), the tightness of the color magnitude relation (Bower, Lucey & Ellis 1992) and the tight correlation between central  $M_{g2}$  line strength and central velocity dispersion  $\sigma$  (Bender, Burstein, & Faber 1993; Ziegler & Bender 1997), indicating an intimate connection between parameters that characterize chemical and dynamical evolution. The small scatter about these relations is difficult to reproduce if there is a wide range of ages among ellipticals. Moreover, distant elliptical galaxies at redshifts  $z \gtrsim 1$  exhibit these same strong correlations (Aragon-Salamanca et al. 1993; Ellis et al. 1997; Stanford, Eisenhardt & Dickinson 1998; van Dokkum et al. 1998b; Barger et al. 1998; Broadhurst & Bouwens 1999), but are brighter overall (van Dokkum & Franx 1996), suggesting an early formation epoch  $z \gtrsim 2$  for an  $\Omega_m = 0.3$ ,  $\Omega_{\Lambda} = 0.7$  universe (van Dokkum et al. 1998a).

Set against this conventional picture are a number of recent studies that suggest that most or many ellipticals have formed continuously over time by mergers that introduce morphological disturbances (Schweizer & Seitzer 1992) and new generations of young stars (Kauffmann & Charlot 1998). Some observations of stellar photometric indices (Prugniel, Golev, & Maubon 1999) and deficiencies of E galaxies at redshifts  $z \lesssim 1$  (Kauffmann, Charlot & White 1996) support significant ongoing evolution, particularly for field ellipticals, but other studies at these redshifts indicate a nearly constant E/S0 space density (Im et al. 1996; Franceschini et al. 1998) and old formation ages (Bernardi et al. 1998).

The age of stars in ellipticals has also been questioned, but progress has been confounded by the age-metallicity conspiracy: youthful, metal-rich and old, metal-poor populations are nearly indistinguishable (Worthey 1997). However, Lick observers have demonstrated that Balmer absorption lines can partially break this age-metallicity degeneracy (Gonzalez 1993; Faber et al. 1995; Trager 1997). By comparing the  $H\beta$  equivalent width (index) and a  $Mg + Fe$  photometric index with expectations from Worthey's evolutionary models, Gonzalez found a wide range of apparent ages in a sample of 40 (mostly field) ellipticals for which the mean age is only  $8 \pm 3$  Gyrs. In addition, stars in the inner regions of these galaxies ( $r \lesssim r_e/8$ ) are about 3 Gyrs younger (and more metal-rich) than those at larger radii. These stellar ages are inconsistent with 13-15 Gyrs, formerly thought to be more likely. The age spread is larger for ellipticals of lower luminosity. Most of the  $H\beta$  equivalent width is contributed by F and G dwarf stars near main sequence turnoff.

## 2. CONTINUOUS STAR FORMATION

In a series of recent papers we have presented detailed models of the evolution of elliptical galaxies with an emphasis on the gas dynamics of the hot interstellar gas (e.g. Brighenti & Mathews 1999a; 1999b). Galactic stars are assumed to form at  $t_{*s} = 1$  Gyr and the de Vaucouleurs structure of the large ellipticals is constructed at  $t_* = 2$  Gyrs. Our calculations successfully reproduce currently observed interstellar (cooling flow) density, temperature and (iron) abundance profiles in massive

ellipticals with a minimum of adjustable parameters.

The global rate that interstellar gas cools can be estimated by dividing the observed (bolometric) X-ray luminosity  $L_x$  by the enthalpy per gram of the gas,  $\dot{M} = (2\mu m_p/5kT)L_x \approx 2.5 M_\odot \text{ yr}^{-1}$  where  $T = 1.3 \times 10^7$  K is typical of large ellipticals ( $m_p$  = proton mass;  $\mu = 0.62$  = molecular weight). The total mass of gas that cools over cosmic time, several  $10^{10} M_\odot$ , is only about 4 - 5 percent of the total baryonic mass currently in stars.

Two of the most perplexing and long standing problems concerning galactic cooling flows are (1) to determine where cooling to low temperatures actually occurs in the galaxies and (2) to determine the final physical disposition of the cooled gas. The dropout or cooling of interstellar gas must occur over a substantial volume of the inner galaxy, but the radial mass profile of cooled gas cannot be predicted from first principles since it depends critically on entropy fluctuations acquired during a variety of complex processes (stellar mass loss, supernovae explosions, magnetic field variations, etc.). To accommodate this uncertainty, we have considered a variety of cooling dropout models in which the hot gas is assumed to cool at a rate  $(\partial\rho/\partial t)_{do} = -q(r)\rho/t_{do}$ , where  $t_{do} = 5m_p kT/2\mu\rho\Lambda$  is the local (constant pressure) cooling time and  $q(r)$  is an adjustable dropout function (Brighenti & Mathews 1999b). We compare computed interstellar properties with currently ( $t_n = 13$  Gyrs) observed interstellar gas in the luminous elliptical NGC 4472. Most of these models are unacceptable because the radial distributions of X-ray surface brightness  $\Sigma_x(r)$ , gas density  $n(r)$  or temperature  $T(r)$  disagree with profiles observed in this galaxy. Among the models considered, the simple constant  $q(r) = 1$  model gave the best results, although the agreement with observed  $\Sigma_x(r)$  was still not perfect; we consider this model again here to estimate the mass dropout in NGC 4472.

Regarding the second perplexing and long standing problem, it has long been speculated that the end product of the cooled gas are low mass, non-luminous stars (Fabian, Nulsen & Canizares 1982; Thomas 1986; Cowie & Binney 1988; Veder, Trester & Canizares 1988; Sarazin & Ashe 1989; Ferland, Fabian & Johnstone 1994). We

have recently reconsidered the star formation process in elliptical galaxy cooling flows and have concluded that the mass of stars in the dropout stellar population probably extends to  $\sim 2 M_\odot$ , i.e. *the dropout population is optically luminous* (Mathews & Brighenti 1999a). As cold gas collects at a cooling site, it becomes gravitationally unstable at this limiting mass, setting a firm upper mass limit  $m_u$  on the IMF for stars forming in the central regions of massive ellipticals. The upper mass limit on the (bottom-heavy) IMF increases only modestly with galactic radius ( $\sim 4 M_\odot$  at  $r \approx r_e$ ) and is almost independent of time during the evolution of the cooling flow for redshifts  $z \lesssim 1$ .

Additional support for the formation of optically luminous stars in galactic cooling flows is provided by the thinness of the fundamental plane. For agreement with observed X-ray surface brightness distributions in ellipticals, most of the mass of cooled gas is concentrated well within  $r_e$  where the relatively small dropout mass can contribute substantially to the central mass and mass to light ratio determined from stellar velocities. If the dropout stellar population is assumed to be non-luminous, Mathews & Brighenti (1999b) have shown that the variation of dark dropout mass among ellipticals causes large, undesirable shifts in the fundamental plane that are incompatible with its observed thinness. However, these perturbations on the fundamental plane may be lessened or removed if the dropout stars are luminous.

### 3. $L_B$ , $B - V$ AND $H\beta$

Star formation in ellipticals is efficient in the sense that the total mass of HII gas and cold neutral or molecular gas at any time are both much less than the total mass of gas that has cooled. Therefore, the star formation rate ( $\Psi_{SFR}$ ) in NGC 4472 is equal to the instantaneous rate that hot interstellar gas cools by radiative losses. The total accumulated mass that has cooled in NGC 4472 since  $t_* = 2$  Gyr,  $M_{do}(t)$ , and  $\Psi_{SFR} = dM_{do}/dt$  are shown in Figure 1a; these are based on the  $q = 1$  model that best fits the X-ray observations of NGC 4472 (Brighenti & Mathews 1999b). The mass dropout  $M_{do}(r, t_n)$  at  $t_n = 13$  Gyrs for this model occurs mostly in  $r \lesssim r_e$  and the total dropout mass is  $M_{do}(t_n) = 4.7 \times 10^{10} M_\odot$ . This

is much less than the total current stellar mass in NGC 4472,  $M_{*t} = 7.26 \times 10^{11} M_\odot$ , determined with  $M/L_B = 9.2$ .

For the purpose of illustration, we assume that the old galactic stars can be approximated as a single burst stellar population having a Salpeter IMF from  $m_\ell = 0.1$  to  $m_u = 125 M_\odot$ . By contrast, the younger dropout stellar population with variable SFR,  $\Psi_{SFR}(t)$ , is assumed to have a Salpeter IMF from  $m_\ell = 0.1$  to  $m_u = 2.5 M_\odot$ . Both of these IMFs are available in single burst format in the 1999 Bruzual-Charlot library for isochrone synthesis spectral evolution (Charlot & Bruzual 1991; Bruzual & Charlot 1993), assuming solar abundance. The total B-band luminosity of the dropout stellar population is

$$L_{B,do}(t) = \int_0^{t-t_*} \Psi_{SFR}(t - \tau) \ell_{B,do}(\tau) d\tau$$

where  $\ell_{B,do}(t)$  is the single burst B-band luminosity per unit solar mass. The luminosity of the background old single burst population is  $L_{B,old}(t) = f_m M_{*t} \ell_{B,old}(t)$  where  $f_m$  is a coefficient of order unity that must be adjusted for agreement with the observed B-band luminosity of NGC 4472 (see below).

The evolution of B-band luminosities and B-V colors are illustrated in Figure 1b and 1c for each stellar population and for their combined radiation. For reference, the redshift  $z = 1$  is shown at time  $t = 6.19$  Gyrs (assuming  $H_o = 65$  km s $^{-1}$ ,  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$ ). We have chosen  $f_m = 1.35$  so that the total B-band luminosity  $L_{B,tot} = L_{B,old} + L_{B,do} = 7.89 \times 10^{10} L_{B,\odot}$ , appropriate for NGC 4472 at distance  $d = 17$  Mpc. Although the dropout population currently contributes about 15 percent of the total B-band light ( $L_{B,do}(t_n) = 1.2 \times 10^{10} L_{B,\odot}$ ), its fractional contribution to the galactic light is quite constant for redshifts  $z \lesssim 1$ . The combined do+old population is only slightly bluer (by  $\delta(B - V) \sim 0.03$ ) than the old population and this difference is essentially constant for  $z \lesssim 1$ . Formally, the  $B - V$  of the combined population indicates an age  $\sim 8.5$  Gyrs that is less than that of the old population alone, 12 Gyrs, but metallicity variations could produce a similar color variation.

To estimate the equivalent width of  $H\beta$  we assume that the line width is similar for both popu-

lations:

$$EW_{\beta,tot}(t) = \frac{\langle ew_{\beta} \ell_B \rangle_{do}(t) + f_g ew_{\beta,old}(t) L_{B,old}(t)}{L_{B,do}(t) + f_g L_{B,old}(t)}$$

where

$$\langle ew_{\beta} \ell_B \rangle_{do}(t) = \int_0^{t-t_*} \Psi_{SFR}(t-\tau) \ell_{B,do}(\tau) ew_{\beta,do}(\tau) d\tau.$$

Here  $f_g(R)$  is the ratio of light from the old to dropout population within projected radius  $R$  normalized to the total ratio of old to dropout light; generally we assume  $f_g = 1$ , corresponding to viewing the total light from both populations.

As an illustration, we use single burst  $ew_{\beta}(t)$  from the 1999 Bruzual-Charlot (BC99) tables appropriate to the IMF of each population. As shown in Figure 2 the dropout population (with  $f_g = 1$ ) reduces the apparent age of the old population by  $\sim 5$  Gyrs, i.e.  $EW_{\beta,tot}(t_n) \approx EW_{\beta,old}(t_n - 5 \text{ Gyrs})$ , in agreement with observations that correlate bluer colors with stronger  $H\beta$  (Forbes & Ponman 1999). For smaller  $f_g = 1/4$ , corresponding to viewing NGC 4472 within  $r_e$ , the apparent age is reduced by  $\sim 8.5$  Gyrs. Actual observations of galactic cores view a fraction of both populations, i.e. the apparent  $H\beta$  age is aperture-dependent. For  $m_u \gtrsim 2$ ,  $ew_{\beta,do}(t)$  and  $EW_{\beta,tot}(t_n)$  are insensitive to  $m_u$ , i.e.  $ew_{\beta,do}(t) = ew_{\beta,old}(t)$  can be assumed. We also used the population code available at the Worthey website to determine both  $EW_{\beta,tot}(t_n)$  and  $(B-V)_{tot}(t_n)$  for a Salpeter dropout IMF from  $m_{\ell} = 0.2$  to  $m_u = 10 M_{\odot}$ . For this model the  $H\beta$  and  $(B-V)$  ages are 8.5 and 9.5 Gyrs with  $f_g = 1$ . These age uncertainties are consistent with ( $\sim 35\%$ ) errors inherent to population synthesis procedures (Charlot, Worthey & Bressan 1996; Worthey 1996).

Clearly, however, the contribution of cooling dropout stars to the spectra of elliptical galaxies can explain the relatively young ages inferred from  $H\beta$  observed in some ellipticals even if the underlying stars are very old.

#### 4. FURTHER DISCUSSION

All massive ellipticals contain cooling interstellar gas so no comparisons with gas-free galaxies can be made. However, since the cooling flow

mass dropout is centrally concentrated within  $r_e$ , the equivalent width of  $H\beta$ ,  $EW_{\beta}$ , should increase toward galactic centers, in agreement with the observations of Gonzalez (1993). Dropout star formation should be accompanied by an ensemble of additional observations at small galactic radii:  $H\beta$  in emission from cooling clouds, enhanced X-ray surface brightness due to dense, locally cooling regions, and lower apparent X-ray temperatures which (with hydrostatic equilibrium) indicate interior masses *less* than the known stellar mass. Such mass discrepancies within  $\sim 0.1 r_e$  are apparent in X-ray observations of bright Virgo ellipticals (Brighenti & Mathews 1997a). Some fraction of the total optical light ( $\sim 15$  percent in Figure 1) in E galaxies comes from the dropout population with  $(M/L_B)_{do} \approx 4 < (M/L_B)_{old}$ . Therefore,  $(M/L_B)$  should vary with galactic radius and produce a shift away from the fundamental plane defined by the old stars alone.

The observed apparent  $H\beta$  age spread among ellipticals is large: 2 to 12 Gyrs in the Gonzalez (1993) sample, 5 to 12 Gyrs in the Fornax cluster (Kuntschner & Davies 1998) and 8 to 12 Gyrs in the Coma cluster (Jorgensen 1999). Such variations can be expected if the cooling dropout profile  $q(r)$  differs among otherwise similar galaxies, represented here with the factor  $f_g$ . But some of the age variation may arise from comparing ellipticals of greatly different  $L_B$ . Interstellar X-ray emission from ellipticals with  $L_B \lesssim 3 \times 10^{10}$  is masked by stellar X-rays, but cooling flows still exist in these faster rotating, low  $L_B$  ellipticals. We have shown (Brighenti & Mathews 1997b) that large cold gas disks may form from cooling flow gas in low  $L_B$  ellipticals similar to the HI disks observed by Oosterloo, Morganti & Sadler (1999). Occasional star formation with normal IMFs and maximal  $EW_{\beta}$  (de Jong & Davies 1997) is therefore expected in low  $L_B$  ellipticals. In luminous ellipticals ( $L_B \gtrsim 3 \times 10^{10}$ )  $m_u$  and  $EW_{\beta}$  will generally be lower due to isolated star formation in the high pressure ISM. But  $L_x/L_B$  varies enormously among bright ellipticals of similar  $L_B$  and  $H\beta$  ages should reflect this same variation since the fraction of mass in the dropout population is proportional to  $L_x/L_B$ . As expected, ellipticals in Gonzalez' sample with  $L_B > 3 \times 10^{10}$  and low  $L_x/L_B$  – NGC 4649, NGC 7619 and NGC 7626 – also appear to be very old ( $\sim 13$  Gyrs). However,

this interpretation is not entirely straightforward; ellipticals with large  $L_x/L_B$  also have larger interstellar pressure which may result in  $m_u < 2$  and lower  $H\beta$  indices. Although  $H\beta$  ages are insensitive to the IMF of the dropout population for  $m_u \gtrsim 2.5 M_\odot$ , as  $m_u$  approaches  $\sim 0.8 M_\odot$ ,  $EW_\beta$  decreases; this is just the range in  $m_u$  anticipated from our model of star formation in luminous ellipticals (Mathews & Brighenti 1999a). The  $H\beta$  index may not vary monotonically with  $L_x/L_B$ .

Although the star formation process described here obviates the need for continued galactic merging to account for the  $H\beta$  equivalent widths observed, we do not claim that recent merging in ellipticals is non-existent or unimportant. We do note, however, that rather few images of ellipticals at small redshift indicate ongoing mergers with gas-rich, star-forming galaxies. But if such regular mergers do generate young stellar populations in ellipticals, it may be possible to detect azimuthal asymmetries in the stellar  $H\beta$  that reflect the orbital plane(s) of the newly-introduced stars. Young stars formed from cooling flow dropout are expected to be symmetrically disposed in the galactic potential, but their orbits may be more radial with narrower lines than those of the old stellar population.

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Fig. 1.— (a) *Solid line*: Cumulative mass of cooled (dropped-out) gas in NGC 4472 in units of  $10^{10} M_{\odot}$ ; *Dashed line*: Star formation rate ( $M_{\odot} \text{ yr}^{-1}$ ) from cooled interstellar gas in NGC 4472. (b) B-band luminosity in  $10^{10} L_{B,\odot}$  for the dropout stellar population (*short dashed line*), the old stellar population (*long dashed line*) and both populations combined (*solid line*). (c)  $(B - V)$  colors of the old stellar population (*long dashed line*) and both populations combined (*solid line*). The *dotted line* is drawn parallel to the horizontal axis. Redshifts  $z = 0$  and 1 are indicated for a cosmology having  $H_o = 65 \text{ km s}^{-1}$ ,  $\Omega_m = 0.3$  and  $\Omega_{\Lambda} = 0.7$ .

Fig. 2.—  $H\beta$  equivalent widths in Angstroms for the dropout stellar population (*short dashed line*), the old stellar population (*long dashed line*) and both populations combined (*solid line*). The *dotted line* is drawn parallel to the horizontal axis. Redshifts are labeled as in Figure 1.



